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BARATROPIC TIDAL PREDICTIONS AND VALIDATION IN A RELOCATABLE MODELING ENVIRONMENT

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IN A RELOCATABLE MODELING ENVIRONMENT

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EXECUTIVE SUMMARY

Under funding from the Office of Naval Research (ONR) and the Naval Oceanographic Office (NAVOCEANO), the Mississippi State University Center for Air Sea Technology (CAST) has been working on developing a Relocatable Modeling Environment (RME) to provide a uniform and unbiased infrastructure for efficiently configuring numerical models in any geographic/oceanic region. With our current emphasis on ocean tidal modeling, CAST has adopted the Colorado University's numerical ocean model, known as CURReNTSS (Colorado University Rapidly Relocatable Nestable Storm Surge) Model, as the model of choice. During the RME development process, CURReNTSS has been relocated to several coastal oceanic regions, providing excellent results that demonstrate its voracity. This report documents the model validation results and provides a brief description of the Graphic User Interface (GUI), with the following salient features:

- CURReNTSS is Colorado University's version of the Princeton Ocean Model incorporating relevant up-to-date physics.

- It provides the capability to assimilate satellite sea surface height (SSH) and tide-gauge data to provide accurate predictions of SSH and depth-averaged currents.

- It has been relocated using the RME GUI to several coastal regions including the West Coast of Africa, San Diego Bay, Yellow Sea, and the North Atlantic Bight.

- The RME GUI provides a user-friendly, automated capability of end-to-end configuration of CURReNTSS in a modular form including Grid Generation, Preprocessing, Remote Model Execution, and Post-Processing.

- CURReNTSS embedded in the RME GUI offers itself as a prototype for transition to NAVOCEANO.

1. INTRODUCTION:

The Navy's warfare theater has moved from blue waters to the littoral regions where engagements are becoming increasingly frequent and significant. Successful execution of such operations in regions of interest requires an all-around quick-and-efficient response that depends on tidal heights and currents information. Because of the difficulties and costs involved in providing real-time measurements of such data, the use of numerical models that can provide accurate predictions of tidal heights and currents has become a practical alternative. For a model to be deployed operationally, it must satisfy some minimum requirements that include:

- The model should be readily relocated in any littoral region of interest;

- It should possess the correct physics so as to reproduce tidal phenomena for all regions of deployment;

- It should be fine-tuned with some minimal but readily available data to provide accurate predictions;

- And finally, the model must be thoroughly validated against available observations under varied geographic and bathymetric regimes.

This report describes one such model, CURReNTSS (Colorado University's Rapidly Relocatable Nestable Tides and Storm Surge) Model, which has been subjected through these rigors. Under ONR and NAVOCEANO funding, the Mississippi State University Center for Air Sea Technology and University of Colorado have developed CURReNTSS, which is currently a two-dimensional tidal model. The model is embedded in a Relocatable Modeling Environment (RME), that provides a user-friendly, interactive interface that allows quick relocation of the model anywhere geographically for which databases and forcing fields exist.

CURReNTSS is an enhanced version of the Princeton Ocean Model that incorporates the relevant up-to-date physics and has been employed in a variety of ocean modeling applications. It assimilates satellite sea surface height (SSH) and tide-gauge data to acquire an accurate nowcast state that leads to accurate predictions of SSH and barotropic currents. During the RME development process, CURReNTSS has been relocated in several coastal oceanic regions, providing excellent results that demonstrate its versatility.

This report documents the model validation results of CURReNTSS from three coastal regions: U.S West Coast (San Diego Bay), Yellow Sea, and the North Atlantic (Bay of

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Fundy). In an earlier study (Mehra et al., 1996), we provided the results of model implementation near the West Coast of Africa. Section 2 provides a description of the numerical model CURReNTSS, and Section 3 discusses the methodology used and results obtained. In Section 4, we give a brief description of the RME GUI, which has been completely revamped to provide an end-to-end automation of the tidal model relocation. Finally, we end by summarizing our conclusions in Section 5.

2. MODEL DESCRIPTION

MSU CAST and the University of Colorado have developed CURReNTSS, a two-dimensional tidal model, embedded in RME that allows for quick relocation of the model to any oceanic region for which bathymetry and forcing fields exist. CURReNTSS is a finite difference, explicit, vertically-integrated barotropic model that assimilates tidal component data from satellite altimetry, coastal tide gages, and from available bottom pressure gages. It is fully non-linear and a sub-component of the NAVOCEANO/CU 3-D operational model. The model uses direct astrodynamical forcing and can incorporate surface forcing (winds stress and pressure fields) from atmospheric models to predict storm surges. The open boundary conditions, obtained from a global run of the model at 1/5th degree resolution, are pre-stored and are readily accessible from the GUI.

The GUI incorporates bathymetry from the ETOPO5 database and provides capability to edit and interpolate it to the model grid. It also allows the modeler to import bathymetry from other databases into the GUI. The model can be run with any number of components including long term and compound tides. It employs a simple SSH data assimilation procedure that replaces the model predicted SSH at pre-determined intervals by a weighted sum of the model prediction and the observed SSH from the tide/bottom pressure at that grid point; the weights are determined a priori. The altimetric tides from Topex Poseidon data, though very accurate, are only yet available for the M2 component. The tide gage data comes from the database at the International Hydrographic Organization (1979), supplemented by the Admirality charts (1993). This database is accessible via the GUI, and tidal components from relevant tidal stations are easily extracted for assimilation in the model.

For applications requiring high-resolution sea levels and currents along a coast, the procedure is to nest a high-resolution local barotropic model at the desired resolution (1-5 km), within a larger domain at a relatively coarser resolution (5-20 km). The nesting approach works best when the bathymetry and surface forcing data bases for each nested domain have the appropriate resolution. The approach then runs the coarse resolution

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CURReNTSS model with tidal boundary conditions derived from the CU global tidal model (that assimilates altimetric and tide gauge data) and atmospheric pressure and wind stress derived from FNMOC products. The output of this coarse model is saved on the boundaries of the nested model at each time step for providing the boundary conditions to the nested model.

Sea level predictions from this fully integrated 2D model have already been validated against tidal station data. The validity of predicted sea levels and barotropic tidal currents from model results is the subject of this report.

3. METHODOLOGY

The barotropic influences weigh heavily on the coastal and shallow waters, and the primary objective herein was to perform validation of sea levels and barotropic tidal currents with available observational data in suitable areas. Two validation studies of the predicted tidal currents were performed at different resolutions in the Yellow Sea and in the North Atlantic. Another validation study for the sea surface levels was performed on the U.S West Coast (San Diego Bay). For these, an enhanced version of the CURReNTSS model was used which is now capable of assimilating altimetry data, e.g., from TOPEX, for improved predictions of tidal elevations and currents.

3.1 Case I: Yellow Sea

3.1.1 Model Setup

For the first study, the CURReNTSS model was implemented in the Yellow Sea at a resolution of 1/5th degree. The gridded domain extended from 117.0 to 131.0 E and from 24.0 to 41.0 North as shown in Fig. 1. The grid resolution resulted in a 71 by 86 grid. It covered the entire Eastern Chinese coast from Taiwan in the south to Anshan in the north and the entire Yellow Sea. The bathymetry was interpolated from a 1/6 degree Korean topographical database and other high resolution accurate databases provided by NAVOCEANO. The GUI provided data from 31 tidal stations in this region, which were assimilated into the model with a fixed weighting parameter (0.9). Global results available via the GUI were used to setup the boundary conditions for the open boundaries, south and east, and eight primary linear tidal constituents were included, namely M2, S2, N2, K2, K1, O1, P1 and Q1.

The model was run for a period of twenty days with a ramp-up lasting five internal periods. The forcing was provided from astrodynamical tides to predict tidal elevations and currents. The external (barotropic) time step was 24 seconds and the bottom drag coefficient was fixed at 0.0015. A snapshot of barotropic tidal currents for a selected time is shown in Figure 2.
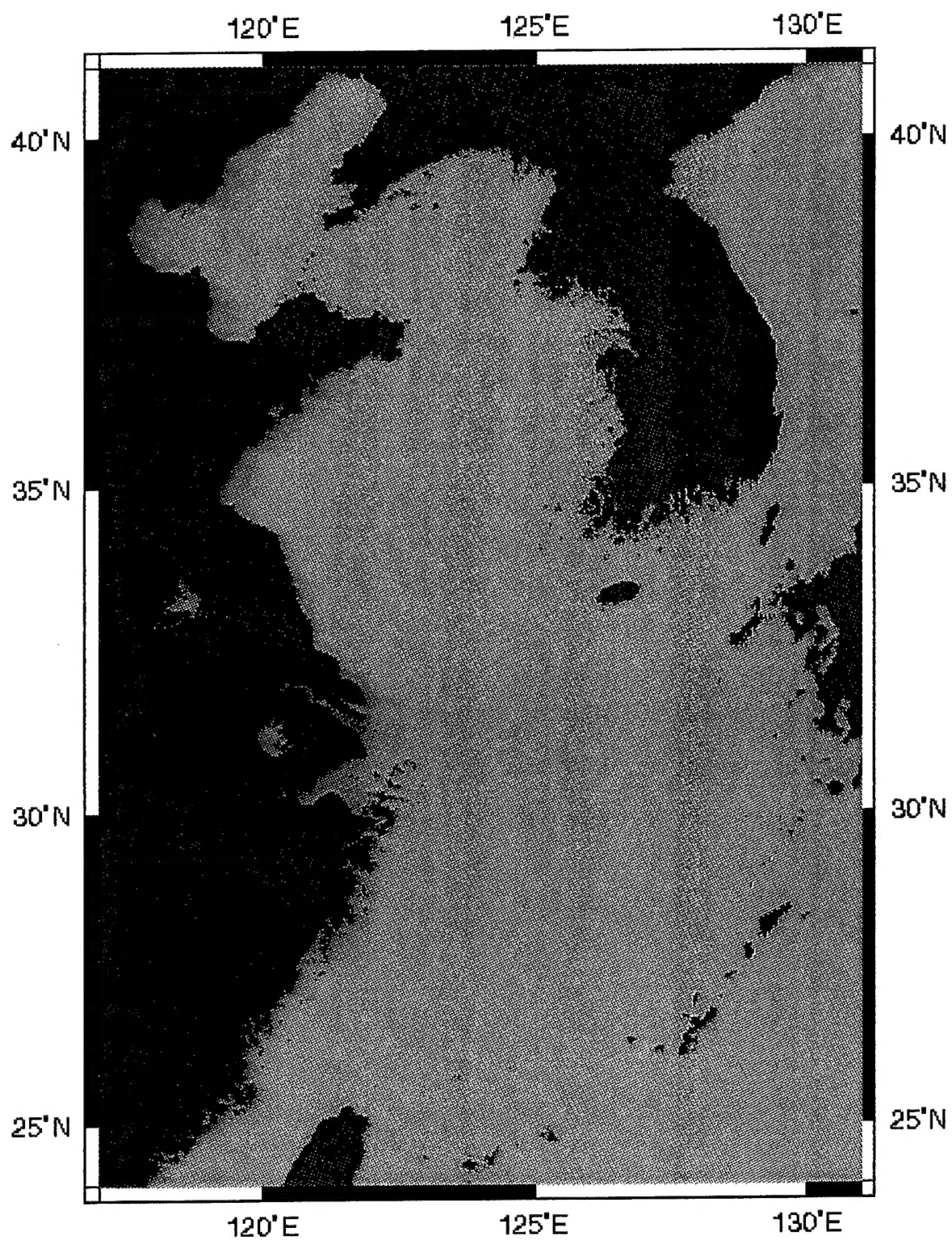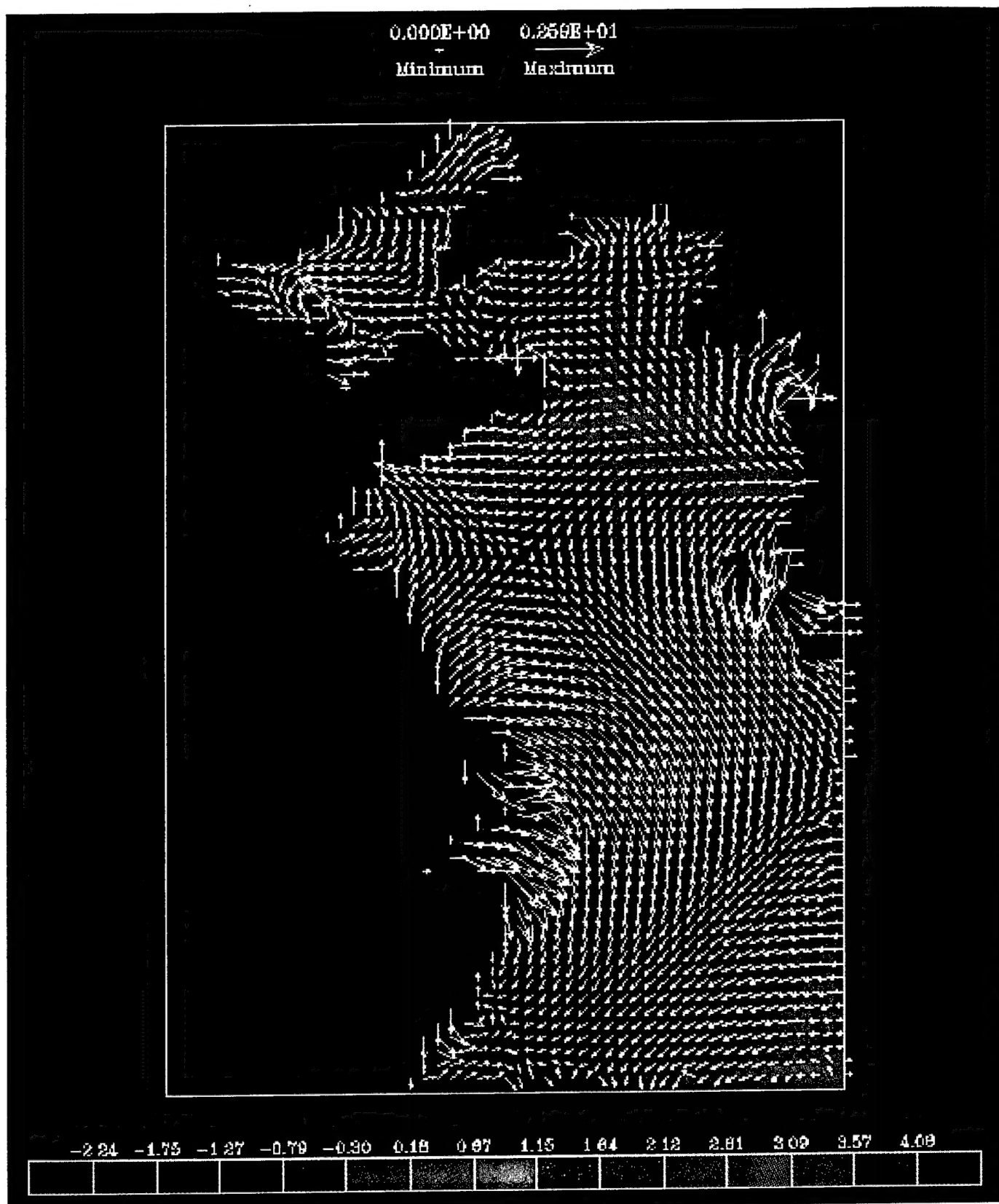
Figure 1: Yellow Sea Domain

Fig. 2: Sanpshot of Barotropic Tidal Currents overlayed on Tidal Elevations (Colored contours) for Yellow Sea.

3.1.2. Results

A time series of induced tidal currents was obtained from the model output and compared against observed tidal currents at the nearest available grid point location. The observed tidal currents were measured using an Acoustic Doppler Current Profiler (ADCP) (at approximately 31.05 North and 126.034 East). The model results compared favorably with the observed values (Figure 3). After the initial ramp-up, the predicted tidal current phases matched well although some discrepancies were found in the magnitudes. These can be attributed to the fact that the model value represents the average value of the current over the grid-cell and not at a fixed point in space. Also, the model predicts depth-averaged currents unlike the observations which were obtained at a fixed depth (approximately at 70 % of the total depth).

3.2. Case II: North Atlantic

3.2.1. Model Setup

The North Atlantic Bight boasts of some of the highest tidal ranges and fastest tidal currents in the world. The CURReNTSS model was run in a nested fashion at two different resolutions. The larger coarser domain at (1/12) degree resolution covered the entire bight from 77.0 W to 63.0 W and from 35.0 N to 45.0 N (see Figure 4). The nested high resolution fine grid at one minute resolution, which mainly covered the Bay of Fundy and some parts of Gulf of Maine, extended from 68.0 W to 64.0 W and from 44.5 N to 45.5 N (Figure 5).

The coarse resolution model was run first for ten days with astrodynamical forcing alone. An accurate bathymetry was generated by fusing ETOPO5, half minute NOS data and an accurate (half minute) USGS topographic database. The boundary conditions were provided from the GUI as before and tidal station data from 144 gages in the region were assimilated into the model. The model results were saved at the boundary of the nested fine grid.

Next, the fine grid model was run with boundary conditions provided from the encompassing coarse model for ten days under similar forcing.The predicted tidal currents at points fixed a priori were used to calculate tidal ellipses and compared against published USGS charts (Moody et al., 1984) data for the North Atlantic. The magnitudes of tidal ellipses (major and mini axes) matched well along with tidal current phases and tidal ellipse orientations.
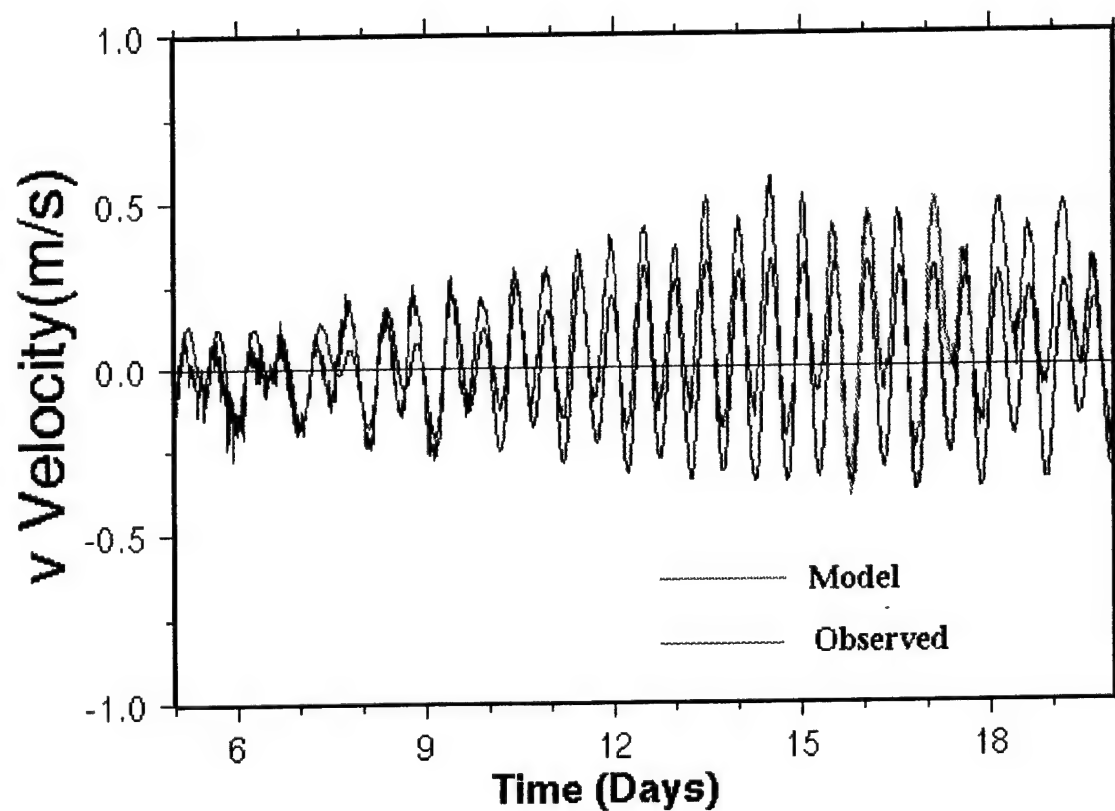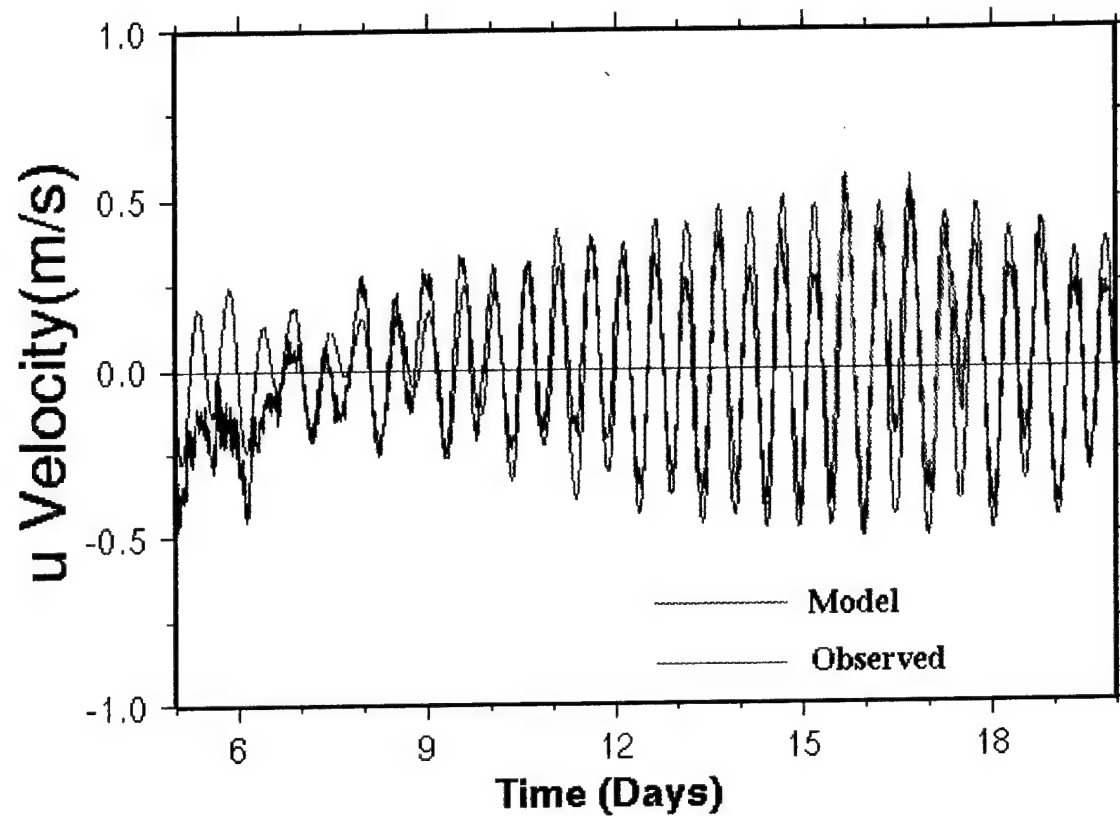
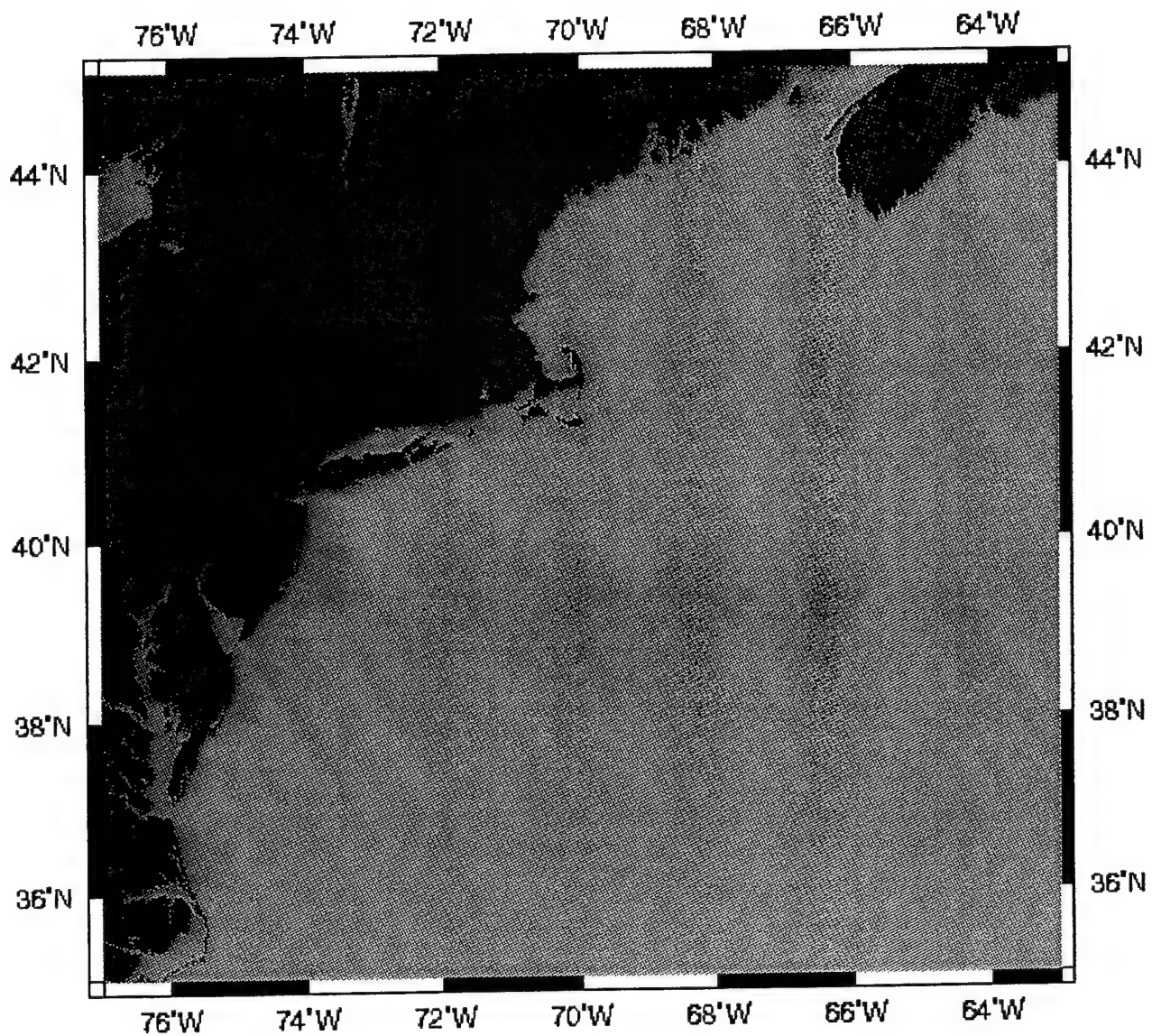**Figure 3:** Comparison of Tidal Current Components in the Yellow Sea .
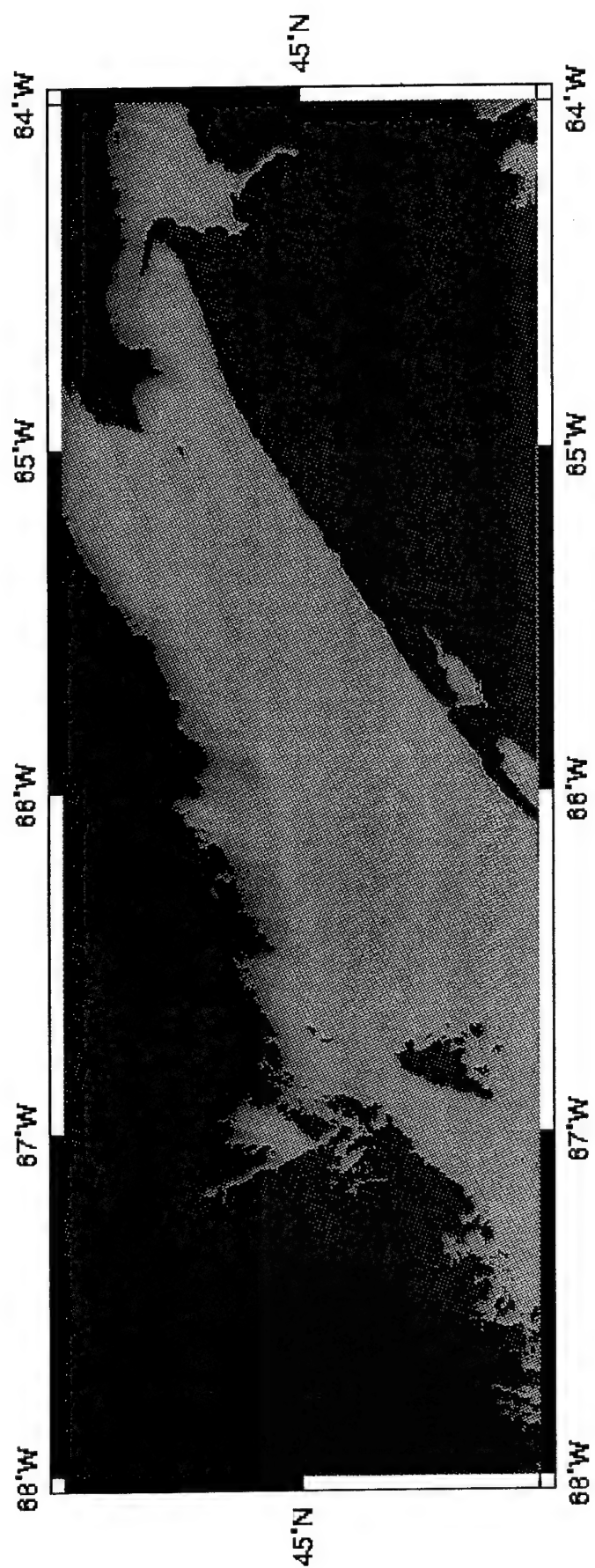
Figure 4: North Atlantic Domain (Coarse)

Figure 5: North Atlantic Domain (Fine)

3.2.2. Results

Comparison of model predicted tidal currents and those obtained from USGS charts at one location in Bay of Fundy (BED60) is shown in Figure 6. As before, the time series for observed tidal currents was obtained at a specific depth (71 m above bottom for BED60), unlike the modeling predictions which are barotropic currents. Also, the modeling results are for currents averaged over a grid cell and not at a single point in the domain. As shown, the predictions underestimates the magnitude of currents for BED60. But, the phase of predictions match well with those of the observed results (within 28 minutes for BED 60).

3.3. Case III: U.S. West Coast

3.3.1. Model Setup

The domain for the coarse grid extended from 119.97 to 116.58 West and from 31.87 to 34.5 North (see Figure 7 (a)). The grid resolution was 5 Kms resulting in a 64 by 59 grid. It covered the California coast including the cities of San Diego in the south to Santa Barbara in the north. The bathymetry was interpolated from an available high resolution accurate database. The GUI provided data from 9 tidal stations in this region which were assimilated into the model with a fixed weighting parameter (0.9). The GUI was also used to setup the boundary conditions for the open boundaries, south and west, and only seven linear tidal constituents were included, namely M2, S2, N2, K2, K1, P1 and Q1. The model was run with both the astrodynamical tides and with surface wind forcing (obtained from COAMPS) to predict tides and storm surge.

The bottom drag coefficient was chosen as 0.0035, and the coefficients of horizontal mixing were fixed at HORCON = 0.02 and AAA = 20.0. The external (barotropic) time step was 8 seconds. In all, 13 locations were chosen for saving time-series output for tidal heights and currents.

The nested fine grid was centered around San Diego Bay at a resolution of 1 km, 117.28 to 117.03 West and 32.32 to 32.82 in the North as shown in Figure 7 (b). The nested domain is also shown "boxed-in" on the larger coarser domain. The total number of grid points at this resolution was 24 by 57. The bathymetry was obtained similarly as above and no tidal station data was assimilated. The boundary conditions for the open boundaries were provided by the output of the coarse model run.

The nonlinear horizontal mixing coefficient, AAA, was changed to 2.0 while other coefficients were kept the same. Because of the higher resolution, the time step was reduced to 5 seconds. Time series output was saved at 5 different locations to compare results with the coarse model output.
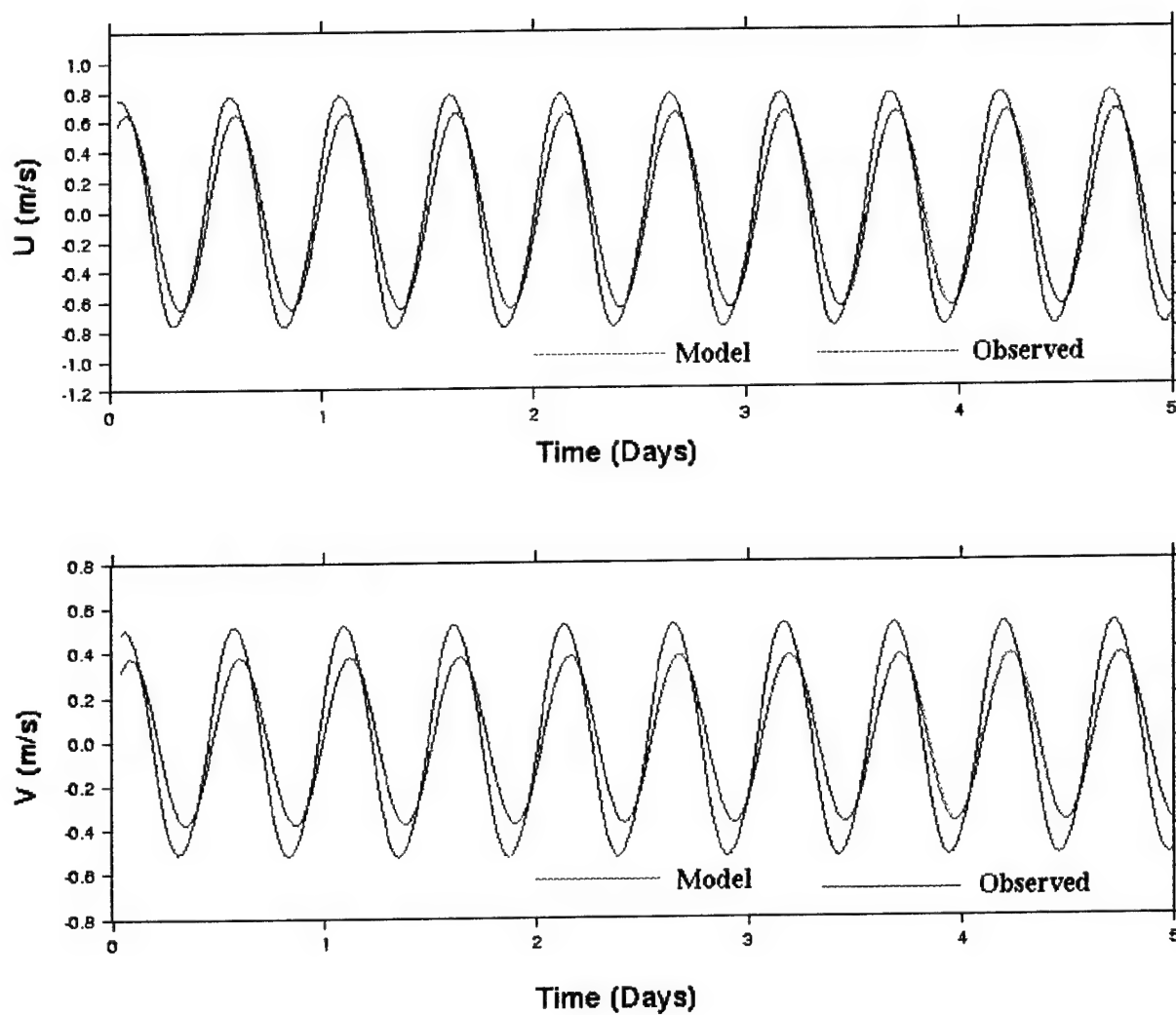
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Figure 6: Comparison of Tidal Current Components in the North Atlantic at Station BED60 (Moody Charts).
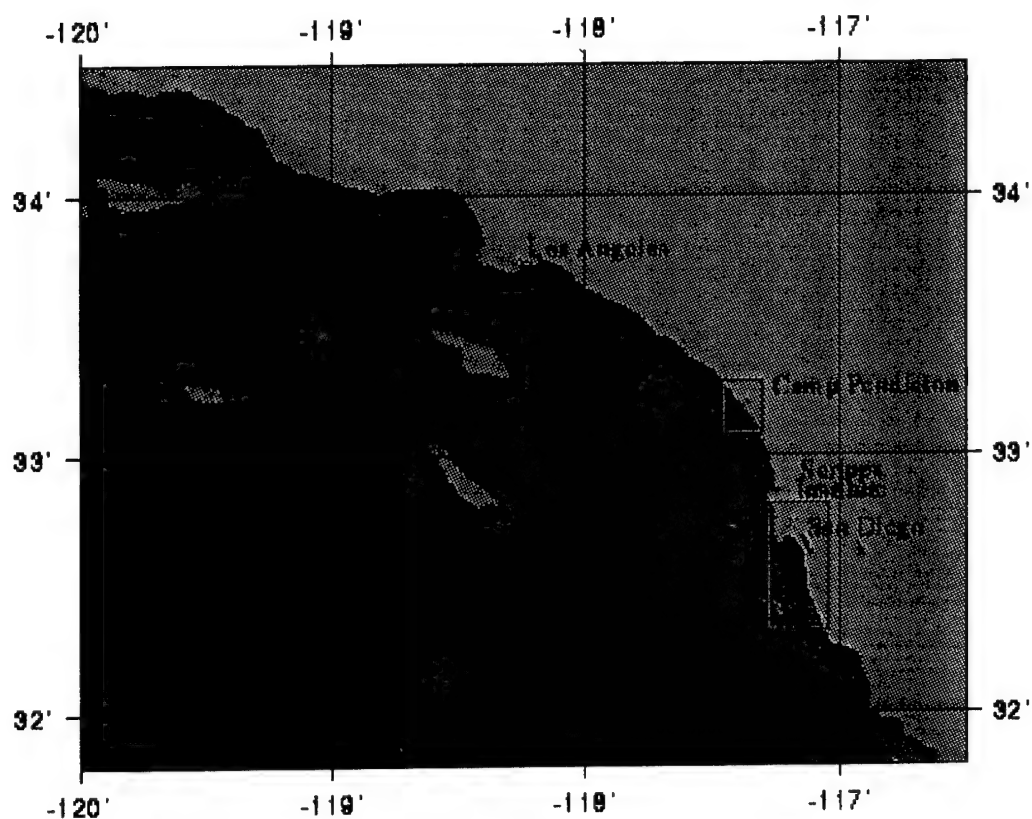
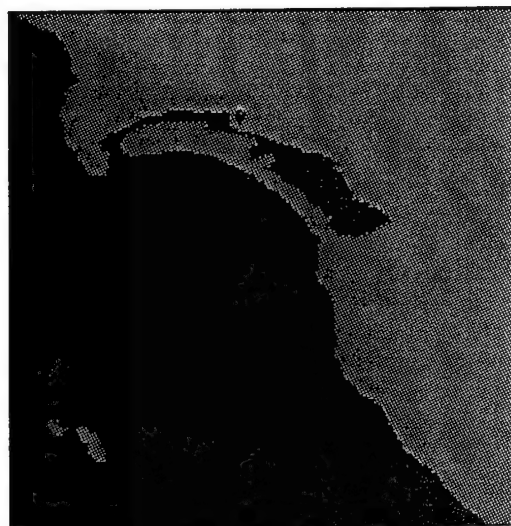**Figure 7 (a): U.S. West Coast (Coarse)**

San Diego Bay (~1 km)

Figure 7 (b): U.S. West Coast (Fine)

3.3.2. Results

Figure 8 shows the time series of wind stress (from COAMPS) and the predicted sea level at one of the grid points located in the fine nested grid near San Diego Bay. It also shows a comparison of observed sea level data from NOS for the time period 3 to 15 January 1995. The data was obtained from a tidal gauge located at 32.71 Degree North and 117.28 West (San Diego Bay), every six minutes. The model was run for the same time period with a one day ramp-up with forcing provided by astrodynamical tides and atmospherical forcing from triply-nested COAMPS numerical model.

The magnitudes of model predicted sea surface elevations compare favorably with the observed sea level elevations except for a large spike which occurred on the fifth day of comparison. This spike corresponds to a significant sea level pressure drop but model results fail to predict it, the reasons for which remain inconclusive. The phase of the predicted sea levels differs from those of the observed value by an avearge of one hour.

4.   RELOCATABLE MODELING ENVIRONMENT (RME) GUI

The many steps and logistics of setting-up a numerical model in a new region of interest are tedious and labor intensive. Much of this effort can be simplified with the modern computer technology. For example, in setting-up a 2-D tidal model, one needs to specify the domain, define the model grid of a specified resolution, select the appropriate bathymetry database and extract the data, edit the bathymetry for errors such as opening-up closed channels, select and extract ancillary data such as the International Hydrographic Office (IHO) tidal station data, make sure the stations fall on a grid point over water instead of land, edit the ancillary data to correct errors, define the model boundaries, specify the model boundary conditions, generate the model header files, and generate the model input and initialization files.

All of these steps need to be completed before the model can be run to obtain the first output. This process can consume anywhere from a couple of days to a couple of weeks depending on the complexity of the domain and data. For more complex, 3-D, data assimilating circulation models, there are also other steps. The user is also faced with postprocessing the model output and managing it systematically.

The main CAST objective is to provide a user-friendly, interactive GUI for an end-to-end implementation of the model including the following modular functionalities discussed below. Their implementation is achieved using the Extensible Distributed Graphical Environment (EDGE) concept under development at CAST. With the current emphasis on
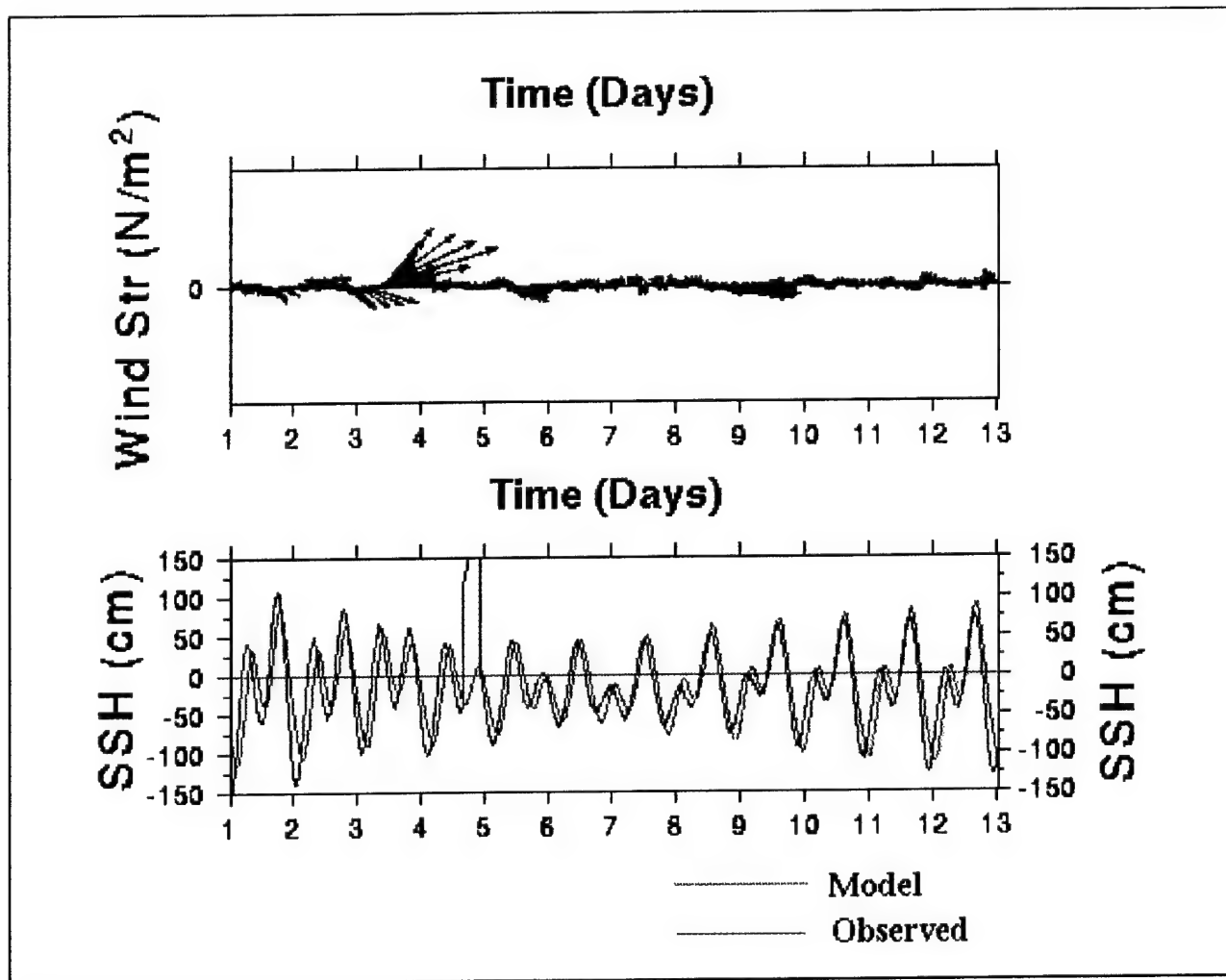
Figure 8: Comparison of Sea Surface Elevations in San Deigo Bay

tidal modeling, the available version is tuned to CURReNTSS. This section provides a brief description of these capabilities.

Grid Generation: The GUI produces a world map for selecting the region to be modeled. The user specifies a uniform grid spacing and two diagonal points on the model domain boundary, and the GUI automatically generates the 'rectangular' grid (actually, grid lengths $\Delta X = \Delta Y$ are specified in degrees, and only for small domains is the grid approximately rectangular). Similarly, the nested grid is embedded in the coarse domain. The GUI automatically creates four files needed for model initialization: (1) (Longitude, Latitude) for each grid point in the coarse grid; (2) (Longitude, Latitude) for each grid point in the fine grid; (3) interpolated bathymetry for the coarse grid; and (4) interpolated bathymetry for the fine grid.

In addition, the GUI creates a file of tidal consituents from tide gauge stations located in the model domain, extracted from the IHO database (1979) supplemented with data from the Admirality charts (1993). Data for each tidal constituent from the selected stations are assimilated into the model integration.

Pre-Processing: This module provides an interactive capability to edit the bathymetry and the IHO station files. The bathymetry editing capability allows one to open or close channels or change depths according to the information available at the time of model execution. Similarly, editing of the IHO station files provides the capability to de-select stations (for data assimilation), if so required, or to move them spatially (essentially altering their locations).

Model Packaging: This step is transparent to the user and his interaction at this stage is not needed. The model packaging module readies data files for porting them to a remote host machine. This involves converting files to netCDF followed by tarring of all source code files and essential data files necessary for successful model execution.

Remote Execution: This module first offers the user an opportunity to modify any of the input parameters, e.g., bottom roughness, model integration time-step, etc. After entering the URL address of the remote machine, the model package is ported to the remote machine. The files are automatically un-tarred, the source code compiled, and submitted to the machine for execution. After the execution is complete, the saved output files are automatically tarred and imported back to the local machine for post-processing, and the user receives the message of run completion on the local machine.

Post-Processing: This module provides the capability of preparing graphics from the saved model output. These include time-series plots at selected locations of: vertically integrated currents including U, V, and speed and sea surface height; snapshots of tidal current vectors with overlying contours of sea surface height which can be used for preparing animations of model results; tables for tidal events for a specified duration; and co-tidal and co-phase plots for all tidal constituents.

5. CONCLUSIONS

CURReNTSS has been successfully relocated and its results (tidal currents and sea levels) validated in varied regions around the globe. This has been facilitated by embedding the model in a user-friendly interactive GUI that helps automate all the tedious and complex tasks necessary to set-up the model, execute it successfully and then post-process the results. The model predictions match well with the limited observational data available in the selected regions. The tidal currents are predicted within a reasonable accuracy, given the restrictions under which the comparisons were conducted. For more accurate tidal current predictions, a fully 3-D baroclinic/barotropic model would be necessary. A 3-D version of the CURReNTSS model is already under development at CU and CAST.

The newly enhanced next generation GUI is based on the EDGE architecture which can be ported and executed on different platforms much more efficiently. Unlike its predecessors, the current GUI architecture is also independent of proprietary third-party software, which further enhances the ease of its distribution and transition capability.

CAST is currently funded under FY97-98 to integrate and implement a 3-D version of the CURReNTSS tidal model in the RME framework. New functionalities will be added to the current GUI to provide vertical (sigma layers) dependence in the datasets for both pre- and post-processing modules. Additional features may also be added to provide further flexibility to the end-user.

A comprehensive RME with a user-friendly GUI will be a valuable tool for Navy modelers. It will facilitate the initial setup as well as the migration of numerical models to different regions of the world with relative ease. The long-term goal for this effort is to integrate all related numerical models, oceanographic and atmospheric (tides, waves, surf, circulation, thermal, and atmospheric forcing) that are regional or local in scale, into the RME GUI. This will not only improve utility but significantly reduce the learning curve for operational users.

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